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August 22, 1963

*Mr. R. W. Schroeder
Space Nuclear Propulsion Office
NASA Lewis Research Center
21000 Brookpark Road
Cleveland 35, Ohio

Subject: WANL-TME-357 dated May 17, 1963, "Preliminary Study of the Effects of the Velocity Limits of Control Drum Actuators Upon Reactor Control System Stability in the Power Range"

Dear Mr. Schroeder:

Transmitted herewith are three (3) copies of the subject report. This report is transmitted for your information.

Respectfully,

H. F. Faught
Program Manager
NERVA Nuclear Subsystem

Enclosures - 3

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WANL-TME-357
(Serial: CD-1630)

PRELIMINARY STUDY OF THE EFFECTS OF THE VELOCITY LIMITS OF CONTROL DRUM ACTUATORS UPON REACTOR CONTROL SYSTEM STABILITY IN THE POWER RANGE

(Title Unclassified)

May 17, 1963

Classification cancelled ~~(or changed to~~ ______)
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by H. T. C. TIC, date SEP 11 1973

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Control Development

Class. Date
JRP U 4-29-82

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Class:

Approved:

F. S. Malick

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ABSTRACT

The effects on reactor control system characteristics of reduced velocity limits in the control drum actuators are studied. It is found that drastic reductions in the velocity limit adversely affect the stability of the temperature control loop and reduce the response of the neutron density control loop. Results are optimistic with regard to reducing the actuator velocity limit.

Future studies are required to specify with certainty velocity limits that would be adequate under all conditions of operation, and to investigate modifications in the neutron density and temperature control loops that would facilitate reduced velocity limits.

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1.0 INTRODUCTION

Present specifications for the control drum dynamic response characteristics include a velocity limit of 45°/second for all drums. This velocity limit has been specified for safety reasons--that is, to restrict the rate of change of reactivity that might be produced by the drums in the event of a control system malfunction. The 45°/second value was based on early Los Alamos studies.

All of the WANL control studies to date have indicated that a 45°/second velocity limit provides more rapid control drum response than is actually required for normal startup and shutdown operation. These studies have been supported by experimental results of the KIWI-B1-B and B-4 tests which required maximum control drum velocities of only 17°/second and 30°/second, respectively. In view of these findings, it would appear to be desirable to consider reducing the present velocity limit. However, there are three important factors relating to safety which could be adversely affected by a reduction in the velocity limit. First is the ability of the control drums to compensate for fast reactivity disturbances produced by hydrogen density changes which accompany a flow system malfunction. Second is the ability to employ a fixed reactor power level scram exclusively to take care of an all-drums-out malfunction.* The third factor is the ability of the reactor control system to respond in a stable manner to transient inputs that drive the control drums into the velocity limit.

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* A discussion of this aspect is contained in "Notes on Control Rod Speed for KIWI-B-1A", by Dr. J. E. Perry, LASL Report N-4-930U.

The first two factors will have to be evaluated in detailed malfunction studies. The importance of the second factor depends on the choice of signals to be employed for reactor scram or cutback. The use of a floating rather than a fixed power scram, for example, would facilitiate a reduction in the control drum velocity limit. Some insight into the third factor has been obtained by the preliminary study outlined below.

The method of achieving the velocity limit in the present G.E. and Bendix pneumatic actuators is shown in Figure 1. This limit is produced by a combination of velocity feedback and position error-signal limiting. The position error signal ϵ is fed into an amplifier which has a built-in limit on its output signal. Thus, the amplifier output voltage E is prevented from exceeding a preselected value E_0. The differentiated output of a potentiometer coupled to the output shaft of the actuator is compared with the amplifier output E. The difference between these two signals e, which can be considered a velocity error signal, is further amplified and used to drive the motor. Because of the velocity feedback signal the actuator motor will attempt to run at such a velocity as to reduce the velocity error to zero. Thus, the actuator velocity will tend to follow the voltage E. In this respect, the voltage E functions as a velocity demand signal. Therefore, a limit on the signal E acts also as a limit on velocity. This does not say, however, that at all times under all conditions the instantaneous actuator velocity will not exceed E. Under transient conditions there may be some velocity overshoot. By and large though, the actuator velocity will follow the signal E.

The following study is the first in a series of studies to determine the effects of reduced actuator velocity limits on the stability of the reactor temperature and neutron density control loops. This first study was carried out to investigate the degree of stability of the present WANL Reference Reactor Control System under transient conditions that drive the reactor control drums into their velocity limits. Subsequent studies will look into the actual nature of the stability limits, and consider modifications to the temperature and neutron density feedback loops of this control system to improve stability characteristics.

The response characteristics of the neutron density control loop alone are considered first and are then followed by an analysis of the overall stability of the reactor control system, including the temperature loop.

2.0 RESULTS

2.1 Log N Control Loop

The effects of the control drum actuator velocity limit on the neutron density loop alone were studied by introducing step changes in the neutron density demand signal that were sufficiently large to drive the drum actuators into their velocity limits. Details of this study are given below.

A simplified analog computer model of the reactor neutron density control loop, shown in Figure 2, simulates operation in the upper power range (80% to 100%). For simplicity, a single-order-lag transfer function was used to generate inherent reactivity as shown, and the log N feedback was linearized. The actuator characteristic chosen was a simple second order lag with a natural frequency fn = 8 cps, and a damping ratio $\zeta = 0.5$. Control drum velocity limits used were 45°/second and 11.25°/second.

The controller gain was adjusted such that with the actuator velocity limit set to 45°/second, a very small step in the log N demand signal, log N_D, produced a slightly oscillatory response in power. Figure 3 indicates the system response to a large, 20% step in N_D (80% to 100%) for the case of a 45°/second actuator velocity limit. The curves show N_D (proportional to power demand), N_M (measured neutron density, proportional to actual power), ΔN (proportional to the change in actual power), θ_D (control drum position demand), θ (control drum position) and θ_D (drum velocity demand). Note that the $\dot{\theta}_D$ signal corresponds to the output signal of the limited amplifier E in Figure 1. The presence of the velocity limit is quite obvious in the $\dot{\theta}_D$ recording. Although there is some overshoot and oscillation in N, the actuator comes out of its velocity limit with no tendency toward loop instability. Figure 4 shows the system response to a return step in N_D (100% to 80%).

The above runs were repeated with the velocity limit reduced by 4 to 11.25°/second. The loop gain was unchanged. Figure 5 shows the system response to the 20% step increase in N_D (80% to 100%). Again, the $\dot{\theta}_D$ recording shows the effect of the velocity limit, and the extent to which the system is driven into the limit. Although there is some overshoot in N, the actuator breaks out of the velocity limit with no difficulty and there is no evidence of any tendency toward instability. Figure 6 shows the response to the return step in N_D (100% to 80%) with the 11.25°/second velocity limit.

It should be noted that the stability of the log N loop has been investigated only for step changes in the demand signal introduced at initially steady state conditions. Indications of stability should not be regarded as conclusive. These first results are not actually representative of conditions that will be encountered in startup and shutdown operations. Future studies of the effects of velocity limits on log N loop stability will include, for example, the effects of reactivity disturbances introduced under steady state and transient operating conditions. There is one conclusion that can be made regarding this study of the log N loop: the velocity limits of the control drum actuators can drastically affect the response characteristics of the log N loop. Although the velocity limits may not cause the log N loop itself to be unstable, the fact that the contribution of the log N loop to the temperature control loop is changed by velocity limit effects makes it necessary to investigate also the stability of the temperature loop under velocity limiting conditions. Accordingly, the effects of velocity limits on the entire reactor control system including the temperature loop were investigated as described below.

2.2 Temperature and Log N Control Loop

The effects of a reduced velocity limit on the response of the reactor temperature control loop in combination with the neutron density loop appear to be more severe than the effects on the neutron density loop alone. These effects on the overall reactor control system were analyzed using the simplified analog computer simulation of the engine and of the WANL Reference Reactor Control System described in WANL-TME-270. The control system for this analog model consists essentially of the log N control loop as shown in Figure 2, and an outer temperature control loop. Figure 7 shows a simplified layout of this control system. The actuator was simulated as previously described.

Two sets of transient operating conditions were considered which could cause the drums to be driven into their velocity limits. First, reactivity disturbances were introduced at various steady state operating power levels; second, the "normal" forty second startup described in WANL-TME-270 (pp 35-41) was re-run with various reduced actuator velocity limits.

2.2.1 Reactivity Disturbances

A reactivity disturbance caused by a run-away of a single control drum was selected as a basis for studying velocity limit effects. A somewhat unrealistic, pessimistic condition was assumed in which the run-away drum initially was stuck in its shutdown position and finally released, proceeding at maximum velocity, out to its maximum reactivity position.

Thus, the drum produced a reactivity transient equal in magnitude to its total reactivity worth. The reactivity transient produced by the run-away drum was approximated by a linear ramp function whose slope was equal to the maximum slope of the actual curve. This simplifying approximation added to the severity of the reactivity disturbance.

A control drum accident of this type may occur with the failing actuator still under the influence of its velocity limit, or in a more drastic case, the accident could include a failure of the velocity limit mechanism.

The results reported in Table I consider only the former case, i.e., the failing actuator runs away at its limit velocity. As indicated in the table, the accident is assumed to occur with the engine operating at 90% power in a steady state condition. The results show almost perfect core exit gas temperature regulation was obtained with the $\pm 10^{\circ}$/second limit.

Run-away drum accidents were simulated for exactly the same conditions as those given in Table 1 except that the run-away drum velocity limit was increased to 360°/second. However, the resulting reactivity disturbances caused a power excursion beyond the operating range of the computer (more than 130% power), and accurate figures for peak overshoot in power and temperature could not be obtained.

The effect of steady state engine power level upon system stability was examined by setting the control drum actuator velocity limits to the values which just barely kept the system from becoming unstable during normal startup and shutdown (+5°/second and - 10°/second). At various steady-state engine power levels, a reactivity disturbance corresponding to an instantaneous single drum run-away accident, was introduced. Table 2 shows that the system stability decreases with power level.

2.2.2 System Stability During Startup and Shutdown

The effect of the velocity limit upon system stability during startup and shutdown as observed on the analog computer is shown in Table 3. By setting the control drum actuator velocity limit to a low level and running the analog engine model through its normal startup and shutdown routines, diverging oscillations were induced. As the actuator velocity limits (both positive and negative) were gradually increased, the rate of divergence of the oscillation and finally the oscillation itself could be eliminated during the engine startup and shutdown phases of operation. As Table 3 indicates, the lowest control drum actuator velocity limit which would not cause instability during normal startup or shutdown was +5°/second and - 10°/second. Figure 8 shows the engine operation during startup with a ± 10°/second control drum actuator velocity limit.

3.0 CONCLUSIONS

The combined temperature and log N control loops become unstable during a reference, 40-second startup when an actuator velocity limit in the order of 5°/second is used. Thus the choice of a practical actuator velocity limit for the reference reactor control system and reference startup schedule must be higher than 5°/second.

The question as to what control drum actuator velocity limit to use for the NERVA engine requires more detailed study before it can be answered satisfactorily. The effects of fast hydrogen density changes have not been considered in the above study. Neither has the nuclear startup phase of operation. Also, the startup and shutdown schedules employed in this study are subject to further verification and revision. Since the above study was made, the reactivity coefficients used in the engine reactor model have been revised. A change of this nature requires a repetition of the work done in this report. Each time significant changes are made in the reactor model or control schedules, the optimum range of actuator velocity limits should be examined in order to keep them up to date. Furthermore, future studies will be made to investigate control system modifications that would improve system stability under transient conditions which drive the control drums into their velocity limits.

Actuator Velocity Limit	Core Exit Gas Temperature Overshoot	Time for Temp Excursion to Disappear	Reactor Power Overshoot	Time for Power Excursion to Disappear	Single Drum Runaway Velocity
$\pm 10^{\circ}$/sec	(immeasurable)	—	1.8%	15 seconds	$+10^{\circ}$/sec
$\pm 45^{\circ}$/sec	60°R	7 seconds	9.4%	18 seconds	$+45^{\circ}$/sec

TABLE 1

Engine Response to Ramp Reactivity Disturbances

Conditions: Steady State Power Level - 90%

Reactivity Disturbance - Single Drum Runaway at Constant Speed

Controlling Actuators - Velocity Limited as Shown

Control Drum Actuator Velocity Limit		Engine Steady-State Power Level	System Stability After Single Drum Instantaneous Drum Runaway Accident
Positive	Negative		
5°/sec	10°/sec	100%	Unstable
5°/sec	10°/sec	70%	Stability marginal
5°/sec	10°/sec	50%	Stable. Response oscillatory
5°/sec	10°/sec	10%	Stable. Response good (non-oscillatory)
10°/sec	10°/sec	100%	Stable. Response oscillatory
10°/sec	10°/sec	70%	Stable. Response good (non-oscillatory)

TABLE 2

Relationship of System Stability to Engine Steady-state Power Level for Strong Control Drum Actuator Velocity Limiting.

System Stability Determined on the Basis of its Response to a Single Drum Instantaneous Runaway Accident.

Actuator Velocity Limit		Stability During Startup	Stability During Shutdown
Positive	Negative		
5°/sec	5°/sec	Diverging oscillation	————
2.5°/sec	10°/sec	Stable (some overshoot)	Diverging oscillation
5°/sec	10°/sec	Stable (small overshoot)	Stable (small overshoot)

TABLE 3

Engine Stability During "Normal" Startup and Shutdown as Effected by the Control Drum Actuator Velocity Limit

Startup and Shutdown Schedule Taken From WANL-TME-270

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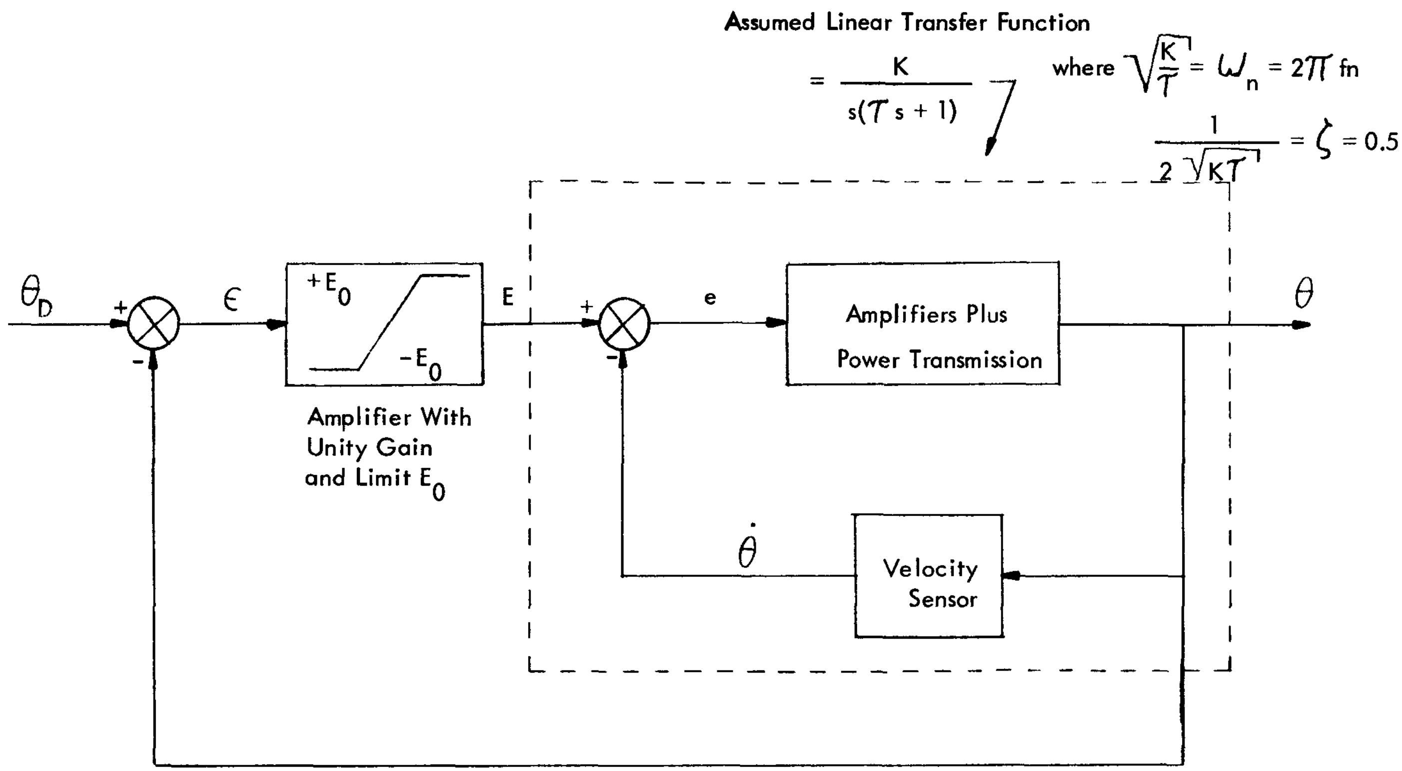

fn = 8 cps
$\zeta = 0.5$

FIGURE 1

BLOCK DIAGRAM OF THE ASSUMED ACTUATOR SHOWING
THE METHOD OF ACHIEVING THE VELOCITY LIMIT

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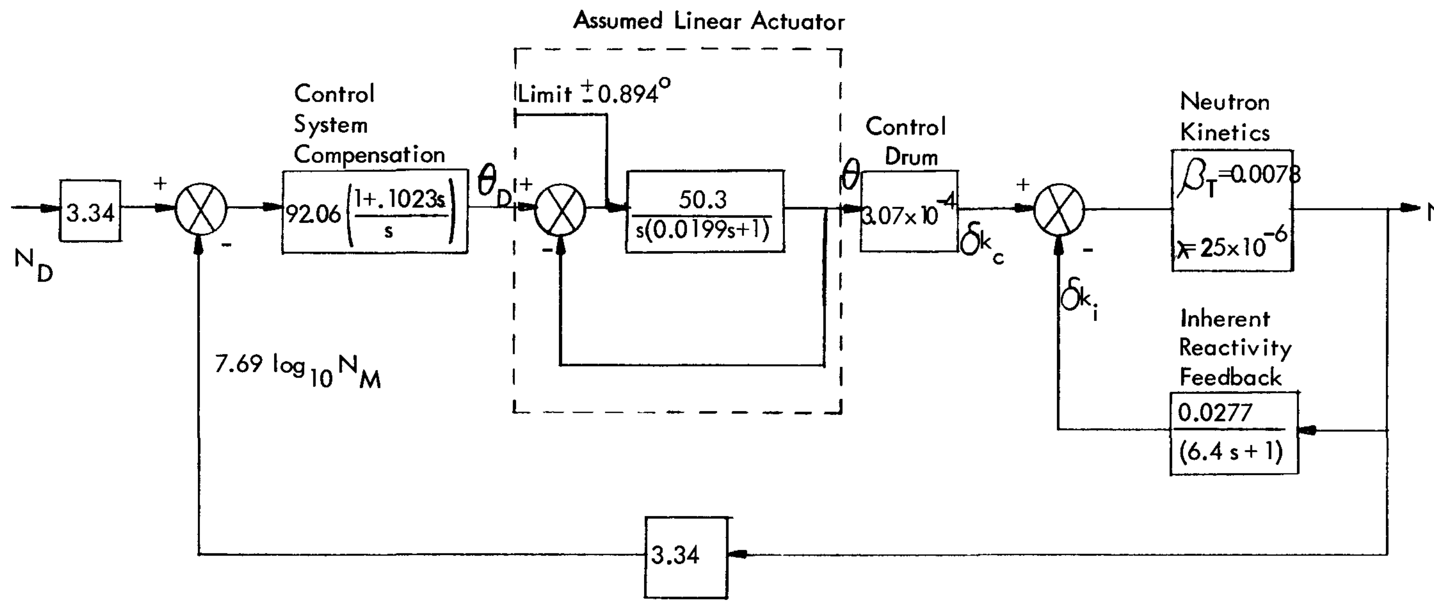

__Feedback Signal Linearization__

exact: $7.69 \log_{10} N$

linearized: $7.69\,\Delta \log_{10} N = 7.69 \dfrac{1}{N\,2.303}\,\Delta N = 3.34\,\Delta N$ (for N=1)

__Actuator Characteristics__

fn = 8 cps

$\zeta = 0.5$

Velocity limits: 45°/sec, 11.25°/sec

FIGURE 2

LOG N CONTROL LOOP LINEARIZED ABOUT THE 100% OPERATING LEVEL

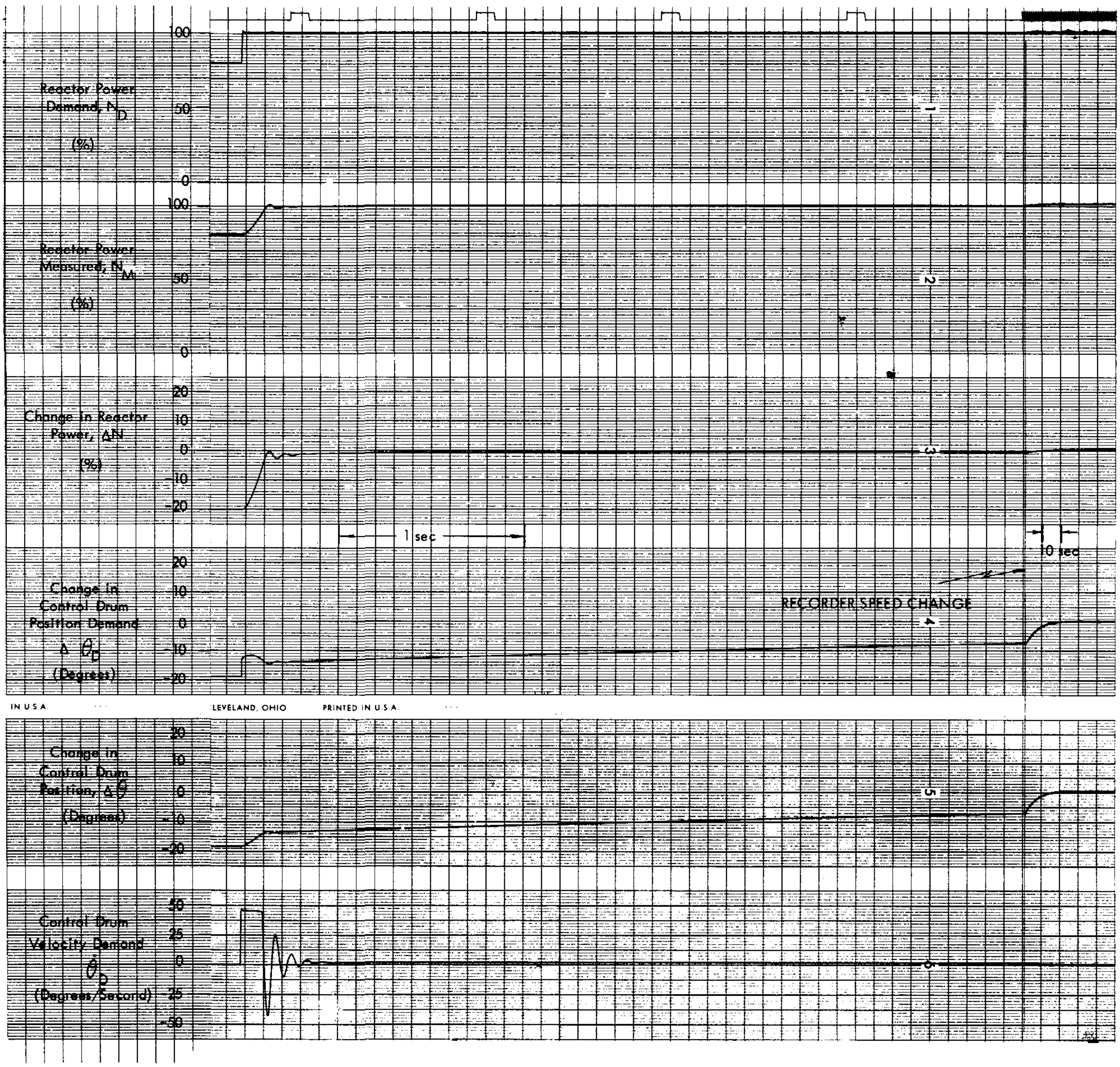

FIGURE 3 RESPONSE OF LOG N CONTROL LOOP TO A STEP INPUT IN N_D (Reactor Power Demand)

Step Magnitude: +20% Rated Power
Initial Power Level: 80% Rated Power
Actuator Velocity Limit: $\pm 45^{\circ}$/second

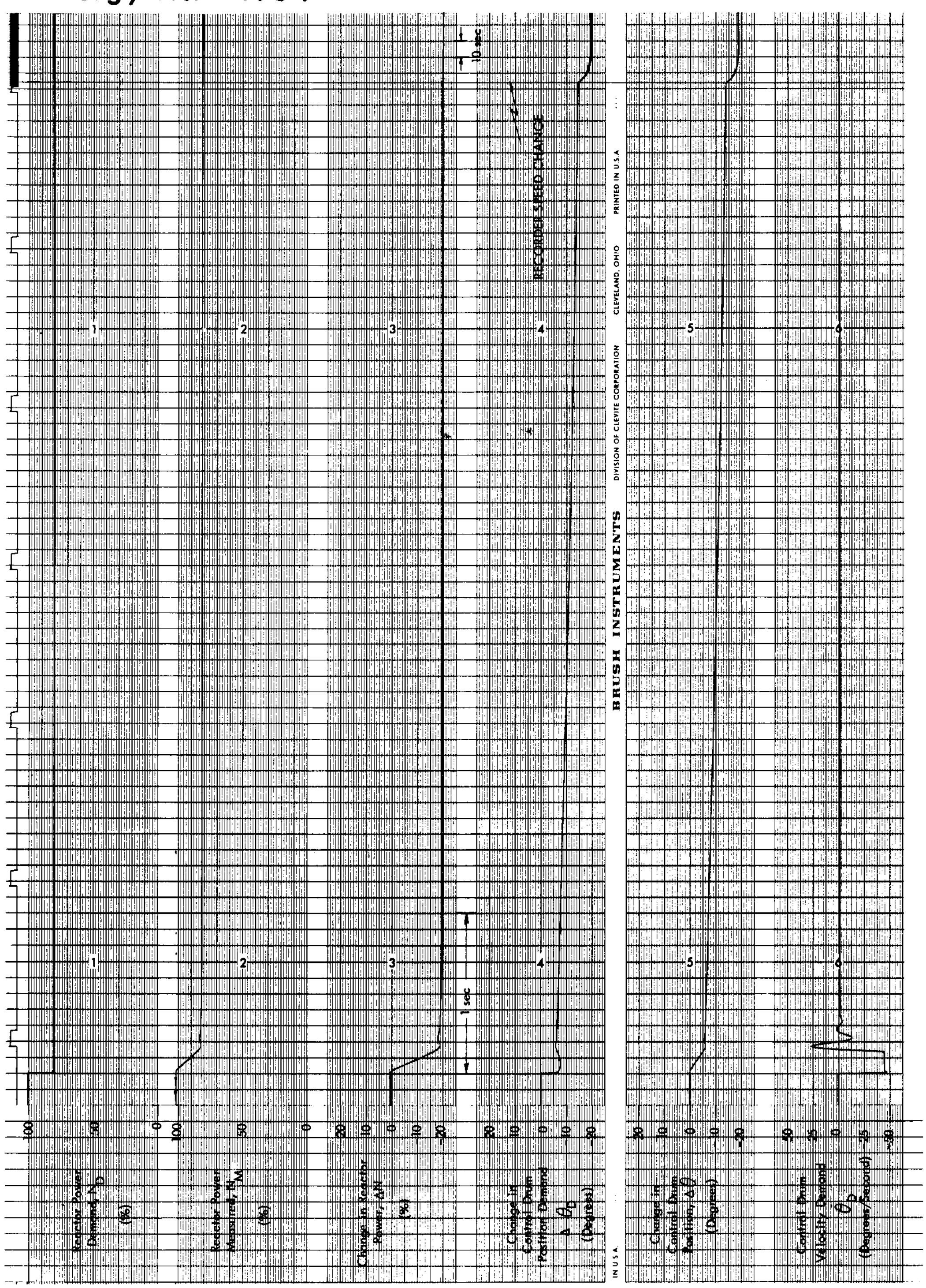

FIGURE 4 RESPONSE OF LOG N CONTROL LOOP TO A STEP INPUT IN N_D
(Reactor Power Demand)

Step Magnitude: -20% Rated Power
Initial Power Level: 100% Rated Power
Actuator Velocity Limit: $\pm 45^{\circ}$/second

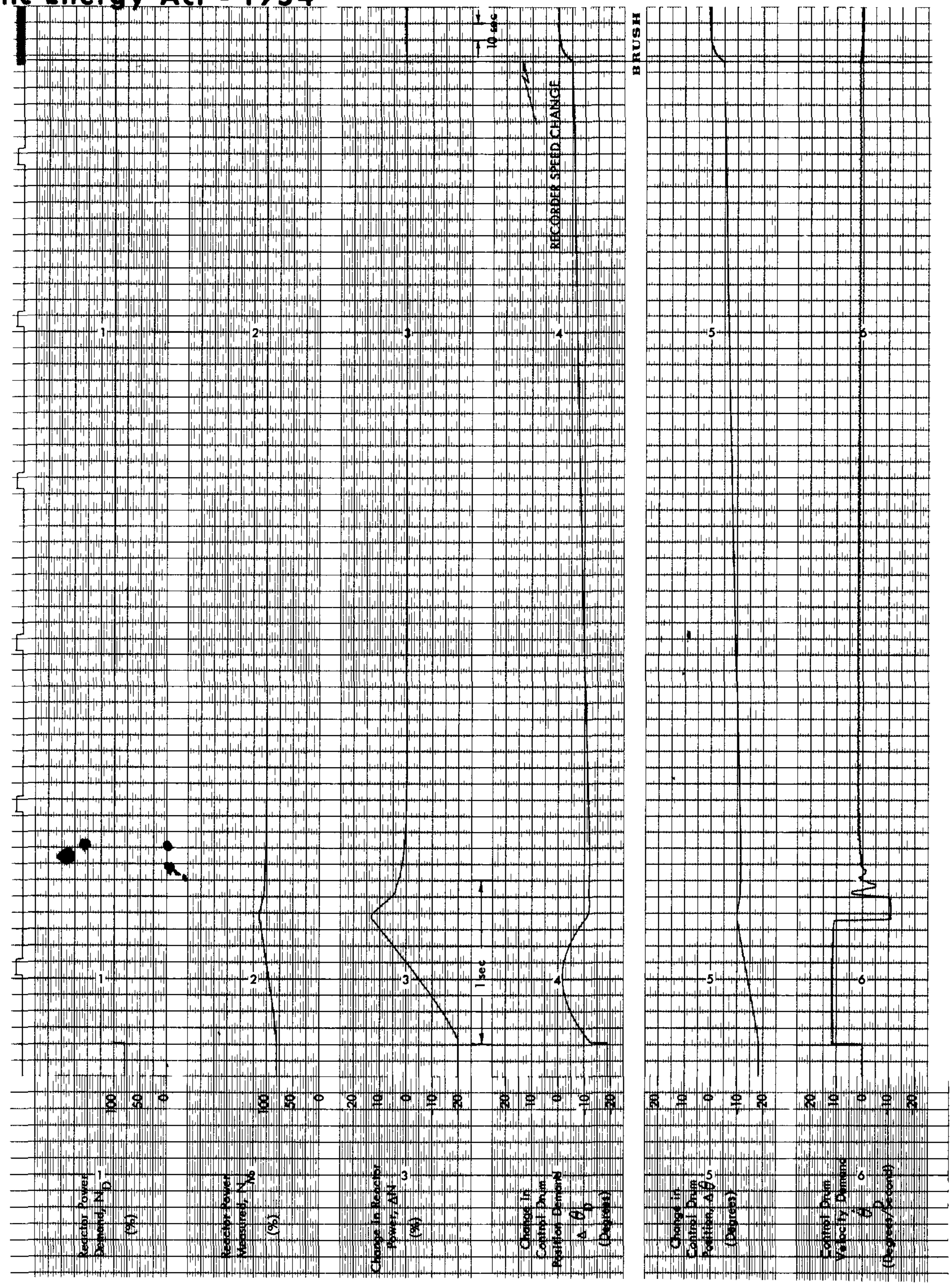

FIGURE 5 RESPONSE OF LOG N CONTROL LOOP TO A STEP INPUT IN N_D (Reactor Power Demand)

Step Magnitude: +20% Rated Power
Initial Power Level: 80% Rated Power
Actuator Velocity Limit: $\pm 11.25^{\circ}$/second

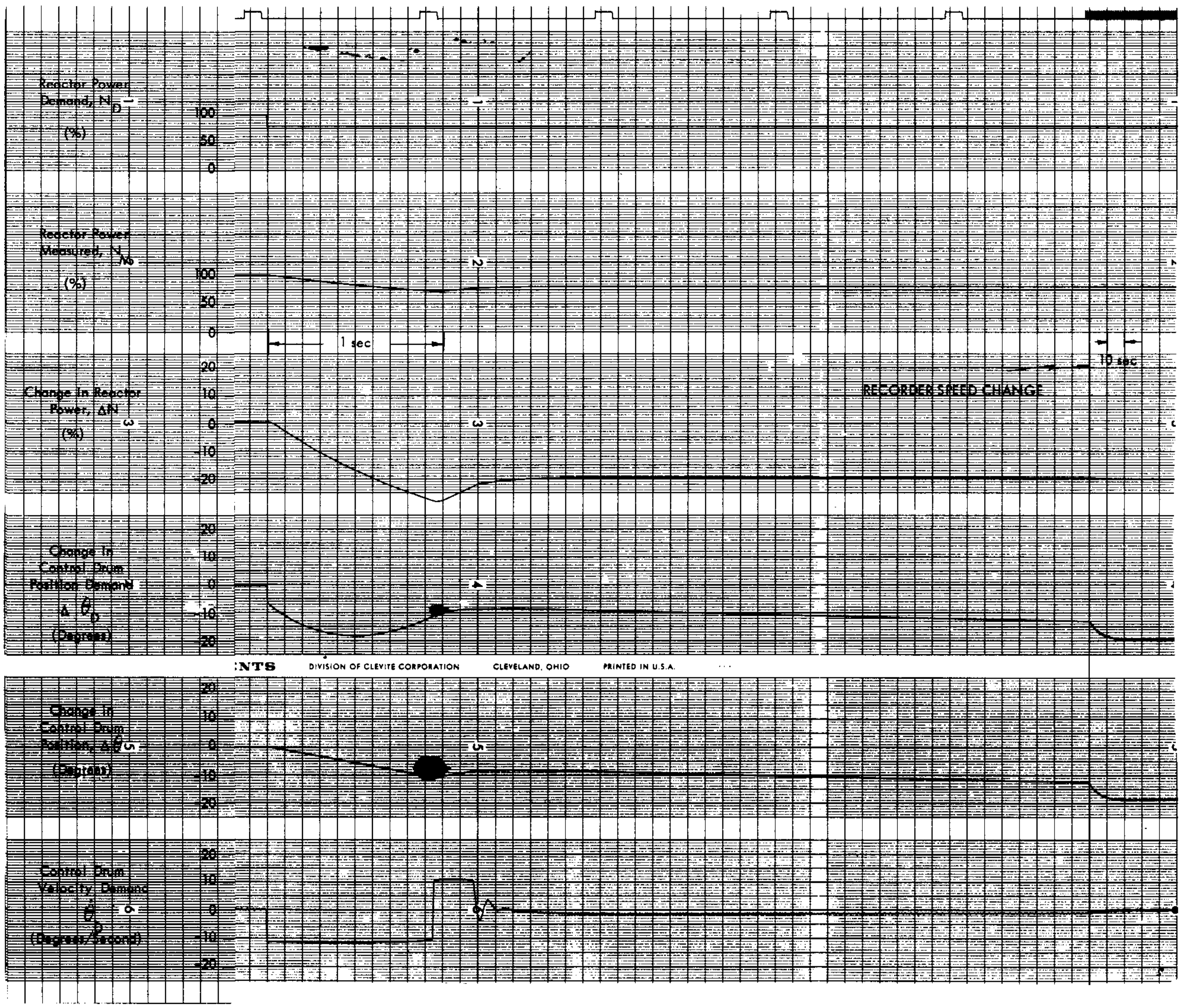

FIGURE 6 RESPONSE OF LOG N CONTROL LOOP TO A STEP INPUT IN N_D (Reactor Power Demand)

Step Magnitude: -20% Rated Power
Initial Power Level: 100% Rated Power
Actuator Velocity Limit: ±11.25°/second

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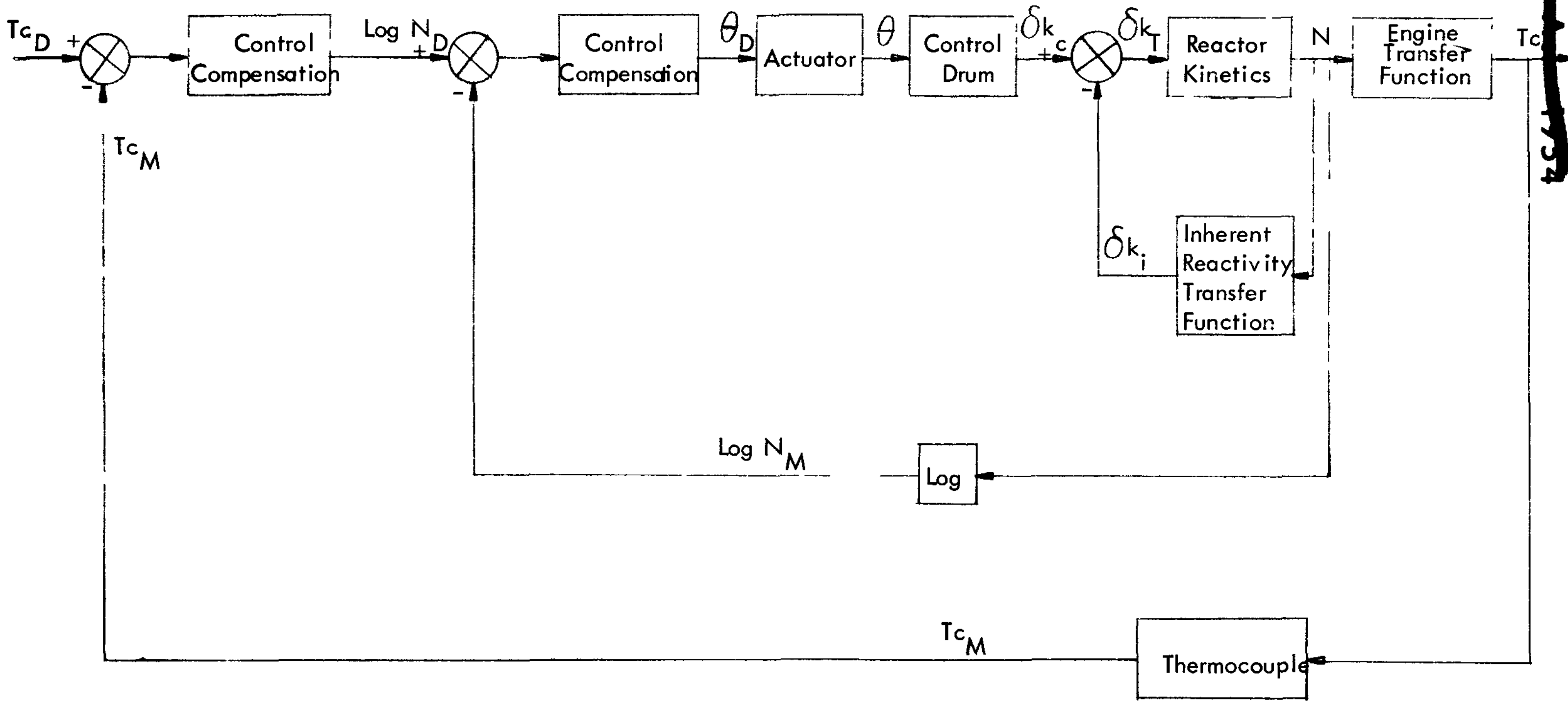

FIGURE 7

COMBINED T_c AND LOG N CONTROL LOOPS

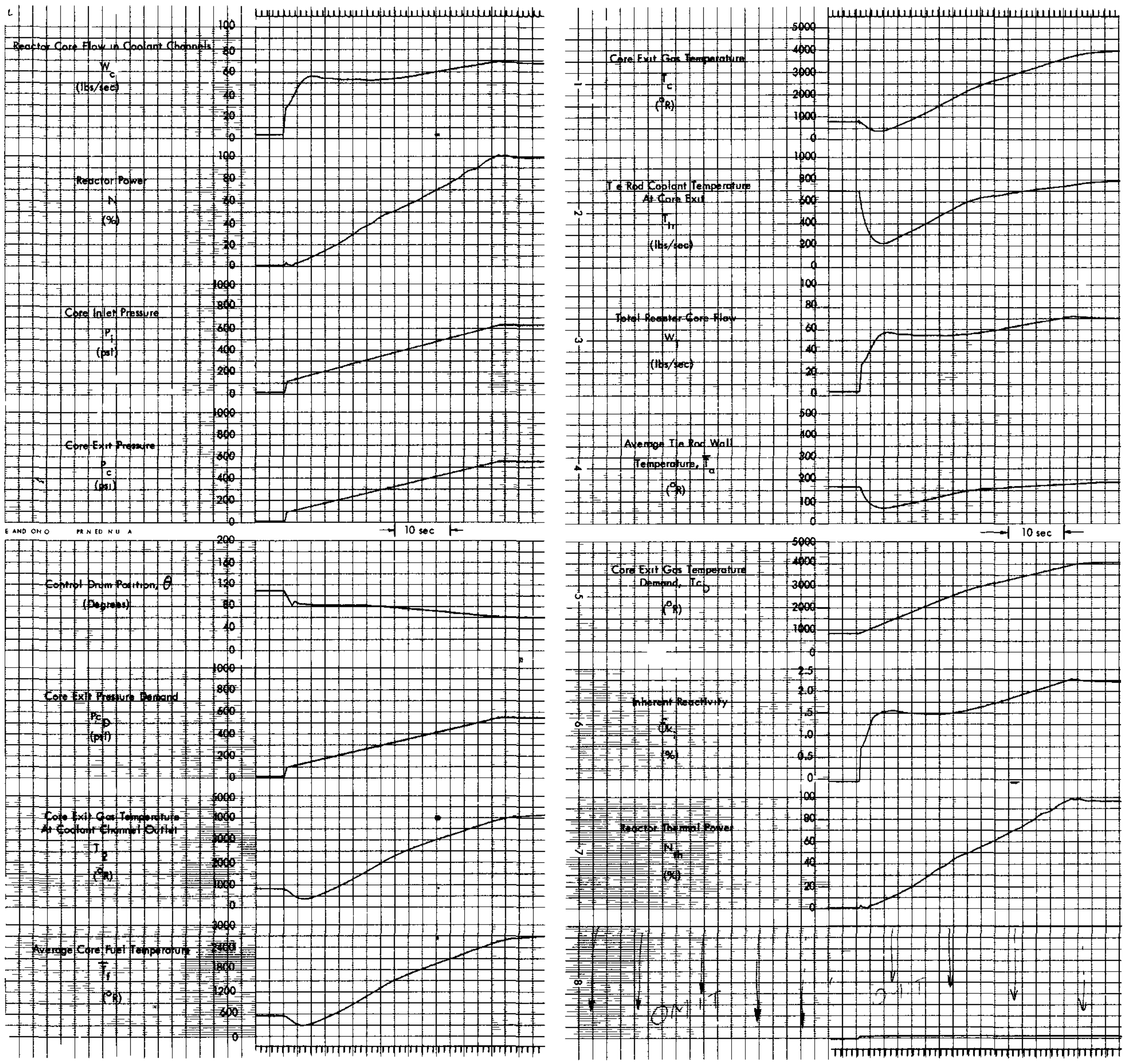

FIGURE 8 ENGINE RESPONSE TO THE REFERENCE 40 SECOND POWER RANGE STARTUP SCHEDULE

Control Drum Actuator Velocity Limit: $\pm 10^{\circ}$/second